

Constraints on the flux of primary cosmic-ray photons at energies $E > 10^{18}$ eV from Yakutsk muon data

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Comparing the signals measured by the surface and underground scintillator detectors of the Yakutsk Extensive Air Shower Array, we place upper limits on the integral flux and fraction of primary cosmic-ray photons with energies $E > 10^{18}$ eV, $E > 2 \times 10^{18}$ eV and $E > 4 \times 10^{18}$ eV. The large collected statistics of the showers measured by large-area muon detectors allows to test the photon fraction as small as a few per mil, thus opening the possibility to probe the chemical composition of cosmic rays at super-GZK energies, density of their astrophysical sources and relevant characteristics of the extragalactic medium, as well as to further constrain exotic new-physics scenarios.

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1. Ultra-high-energy (UHE) cosmic-ray photons are secondary particles naturally expected to be produced by energetic protons and nuclei interacting with various backgrounds at acceleration sites or/and along their trajectories towards the Earth [1].

While the observation of the suppression of the cosmic-ray flux at energies $E \gtrsim 6 \cdot 10^{19}$ eV by the High Resolution Fly's Eye (HiRes) [2] and by the Pierre Auger Observatory (PAO) [3] and lack of the Galactic anisotropy at $E \gtrsim 10^{19}$ eV suggest that the most energetic cosmic particles have the extragalactic origin, the chemical composition of these particles is still largely uncertain. While the HiRes measurements of the mean depth of air-shower development [4] and of its fluctuations [5] are fully consistent with pure proton composition, a similar analysis of the PAO data [6] suggests a substantial fraction of heavy primaries at $E \gtrsim 10^{19}$ eV. The latter possibility is supported by the Yakutsk muon data [7] and by the studies of the shower front structure by PAO [6]. Therefore, independent tests of the chemical composition at extreme energies are of high importance.

One of these tests is provided by a search for primary photons with somewhat lower energies, $E \gtrsim 10^{18}$ eV. Indeed, both protons and heavier nuclei with energies $E \sim 10^{20}$ eV experience intense interaction with cosmic background radiations, especially with microwave (CMB) and infrared (IRB) photons. The processes involved in these interactions are however very different. Interactions of a *proton* at $E \gtrsim 7 \times 10^{19}$ eV with CMB photons lead to efficient pion production through baryon resonances. The proton loses about 20% of its energy per each 5 Mpc of travel (see, e.g., [8]). This energy drag implies the Greisen–Zatsepin–Kuzmin (GZK) cutoff [9, 10] in the cosmic ray spectrum at highest energies.

Further decays of neutral pions produced in these interactions provide with the secondary photon flux at energies $E \gtrsim 10^{18}$ eV (so-called GZK photons) [8, 11]. On the other hand, the dominant interaction channel for *heavier nuclei* is the photodisintegration on the IRB photons. The protons emerged in this reaction may further photoproduce on CMB; however, their energies are typically smaller than the resonance threshold. As a result, both the spectral suppression is less pronounced [9, 10, 12] and the secondary photon flux is much smaller [13]. Therefore, the observation of relatively large photon flux at energies $E \gtrsim 10^{18}$ eV would speak in favor of the absence of heavy nuclei at highest energies. UHE photon spectrum at the Earth depends both on original spectrum at the sources and on details of travelling through the Universe. Thus, if measured, photon component gives a possibility to probe acceleration mechanism operating in the sources, their density and relevant characteristics of extragalactic medium (photon background, magnetic fields, etc.)

On the other hand, the study of UHE photons is a powerful tool for constraining new-physics models. One example is provided by models with superheavy dark-matter particles. Originally suggested [14] to explain the high energy cosmic ray events beyond the GZK-cutoff mostly due to the AGASA excess [15, 16], the models *per se* are not ruled out. The superheavy-particle production in the early Universe is naturally driven by gravitational expansion at the post-inflationary preheating stage [17, 18]. This mechanism is quite generic and is capable of explaining dark matter, if particles are long-lived enough. The superheavy particles can be naturally unstable due to either gravity-suppressed couplings [14, 19] or non-perturbative quantum field theory processes [20]. Dark-

matter particles are collected in galaxies and their decays contribute to the observed cosmic-ray flux. Generally, a substantial fraction of the decay products are photons, which in the energy range of interest, $E > 10^{18}$ eV, penetrate straight through the Galaxy. The distribution of arrival directions of these photons over the celestial sphere is expected to exhibit anisotropies (cf. Ref. [21]), reflecting the dark-matter distribution in the Galaxy and the Local Group. Searches for the UHE photons, as well as neutrinos, give a unique possibility to hunt for the superheavy dark matter. One more class of exotic relics to be searched for with cosmic rays are topological defects. These objects emit highly energetic particles contributing to the flux of UHE cosmic rays (see e.g. [22, 23]) and UHE photons were suggested [24] as a signature of this process.

With the help of UHE photons, one may also constrain astrophysical models of the cosmic-ray origin which involve new physics at the propagation stage. In particular, both the spectrum and the chemical composition of cosmic rays are changed in models with violation of the Lorentz invariance [25]. UHE cosmic rays are particles with highest Lorentz-boost factors, and hence the very place to probe these models. Photon fraction at highest energies is sensitive to parameters violating Lorentz invariance, and upper limits on the former severely constrain the latter [26]. Finally, photons with energies above $\sim 10^{18}$ eV might be responsible for cosmic-ray events correlated with BL Lac type objects at the angular scale significantly smaller than the expected deflection of protons in cosmic magnetic fields and thus suggesting neutral primaries [27, 28] (see Ref. [29] for a particular mechanism).

In this *Letter* we present the analysis of extensive air showers observed by The Yakutsk Extensive Air Shower Array (hereafter Yakutsk), which yields the strongest limits on photon flux and photon fraction in cosmic rays at energies $E > 10^{18}$ eV, $E > 2 \times 10^{18}$ eV and $E > 4 \times 10^{18}$ eV. These limits enter the region interesting both for highest-energy astrophysics and tests of extragalactic backgrounds as well as for searches of new physics.

2. The key idea of the method is the event-by-event comparison of observed muon densities in air showers with those in simulated gamma-ray induced showers which have the same scintillator energy deposit and the same arrival direction as the observed ones. The method is described in detail in Ref. [30]; it has been previously applied to Yakutsk and AGASA muon data at highest energies [31, 32]. One of the advantages of the method is its independence both from the energy-reconstruction procedure used by the experiment and from the Monte-Carlo simulation of hadronic air showers: we use simulated gamma-ray induced showers which are mostly electromagnetic and are therefore well understood and we

select the simulated showers by the observable scintillator signal and not by the energy (effectively estimating the energy of each event in the assumption of the photon primary).

The Yakutsk extensive-air-shower array is equipped with five muon detectors of 20 m² area each with threshold energy 1 GeV for vertical muons. At present, it is the only installation in the world which is equipped with muon detectors and is capable of studying cosmic rays with energies above 10^{18} eV.

For the present study, we use the sample of events satisfying the following criteria:

- 1) the event passed the selection cuts for the spectrum reconstruction;
- 2) the reconstructed core location is inside the array boundary;
- 3) the zenith angle $< 45^\circ$;
- 4) the reconstructed energy [46] $E_{\text{rec}} \geq 10^{18}$ eV;
- 5) the reconstructed shower axis is within 300 m from an operating muon detector.

The data set contains 1647 events and corresponds to the effective exposure of $7.4 \times 10^8 \text{ km}^2 \cdot \text{s} \cdot \text{sr}$.

By making use of the empirical muon lateral distribution function [33], we calculated, for each event, the muon density at 300 m from the shower axis, $\rho_\mu(300)$, which we use as the composition estimator. Individual detector readings were evaluated from the raw data reanalyzed for this study. Statistical errors of these detector readings were estimated on the case-by-case basis (details of the reanalysis of the Yakutsk muon data will be presented elsewhere). The dominant contribution to the statistical error of $\rho_\mu(300)$ comes from the uncertainty in the determination of the shower axis (for which we use the geometric reconstruction from the main scintillator array). The overall uncertainty of $\rho_\mu(300)$ varies from $\sim 15\%$ to $\sim 40\%$ for individual events.

We apply the event-by-event analysis following Ref. [30] and estimate, for each event, the probability that it has been initiated by a primary photon with energy in the range under study. To this end, we use a library of photon-induced showers with different energies and arrival directions, of which we select those with the same scintillator signal and zenith angle as the observed event, up to reconstruction errors (a detailed description of the method is presented in Ref. [30]). Since all events in the sample have reconstructed energies below 10^{19} eV, we do not expect azimuthal-angle dependence of the shower properties due to geomagnetic cascading; therefore we require consistency between the arrival directions of the observed and artificial showers in zenith angle only. To obtain the limit on the flux of primary photons, we slightly modified the technical part of the procedure of Ref. [30]. Let F_γ be the integral flux of primary photons over a given energy range. Then we expect

to detect

$$\bar{n}(F_\gamma) = F_\gamma A(1 - \lambda)$$

photon events on average, where A is the exposure of the experiment for a given dataset and λ is the fraction of “lost” photons. Let $\mathcal{P}(n)$ be the probability to have n photons in a dataset (calculated from data following Ref. [30]). To constrain the flux F_γ at the confidence level ξ one requires

$$\sum_n \mathcal{P}(n) W(n, \bar{n}(F_\gamma)) < 1 - \xi,$$

where $W(n, \bar{n})$ is the Poisson probability to observe n particles for the average \bar{n} .

To simulate the shower library, we used CORSIKA 6.611 [34] with FLUKA 2006.3 [35] as a low-energy hadronic interaction model and EPOS 1.61 [36] as a high-energy model. This choice of the hadronic models corresponds to the highest muon density and therefore provides a conservative limit on the gamma-ray flux; however we checked that the difference in expected muon density between EPOS 1.61 and QGSJET II [37] is negligible for photon showers. We used thinning (10^{-5}) with weight limitations [38] to save computational time. The response of the scintillators was simulated with GEANT in Ref. [39].

Below, we present limits on the fraction of gamma rays and on the absolute gamma-ray flux. The flux limits do not depend on the choice of hadronic interaction model used in simulations, nor on the energy reconstruction used in the experiment; the only assumption is that electromagnetic showers are simulated correctly. The fraction limits depend on the energy scale assumed for non-photon primaries.

3. The upper limits on the observed flux and fraction of primary gamma rays are summarized in Table I. We compare the limits with those from previous works in Fig. 1 (for the gamma-ray fraction) and Fig. 2 (for the gamma-ray flux).

The sensitivity of plastic scintillators to electromagnetic showers, strong discriminating power of large-area muon detectors, 25-year exposure and a sophisticated analysis led up to the most stringent limits on the primary photon flux at energies above 10^{18} eV and 2×10^{18} eV. These limits challenge previously allowed new-physics models and start to fill the gap between limits on the diffuse gamma-ray flux at $\sim 10^{16}$ eV and $\sim 10^{19}$ eV. The *flux* limits do not depend on the energy reconstruction used by the experiment (a reconstruction in assumption of primary photons is used), nor on the simulations of hadronic showers. The *fraction* limits also use the energy estimation in assumption of primary photons and also do not rely on simulation of hadronic showers; however they depend on the assumed energy estimation of

$E_{\min},$ eV	95% CL upper limits			
	$F_\gamma,$ $\text{km}^{-2}\text{sr}^{-1}\text{yr}^{-1}$	ϵ_γ	ϵ_γ ($E_{\text{rec}} + 30\%$)	ϵ_γ ($E_{\text{rec}} - 30\%$)
(1)	(2)	(3)	(4)	(5)
10^{18}	0.22	0.004	0.003	0.006
2×10^{18}	0.13	0.008	0.005	0.018
4×10^{18}	0.13	0.041	0.022	0.108

TABLE I: Upper limits (95% C.L.) on the integral flux F_γ of photons with $E > E_{\min}$ and on the fraction ϵ_γ of photons in the total integral flux of cosmic rays with $E > E_{\min}$. The flux limits (col. (2)) do not depend on the energy reconstruction procedure; the fraction limits are given for the assumption of correct energy reconstruction for non-photon primaries (col. (3)) and for the supposed overall shifts of $\pm 30\%$ for non-photon primaries (cols. (4),(5)), which correspond to the window of the systematic error [40].

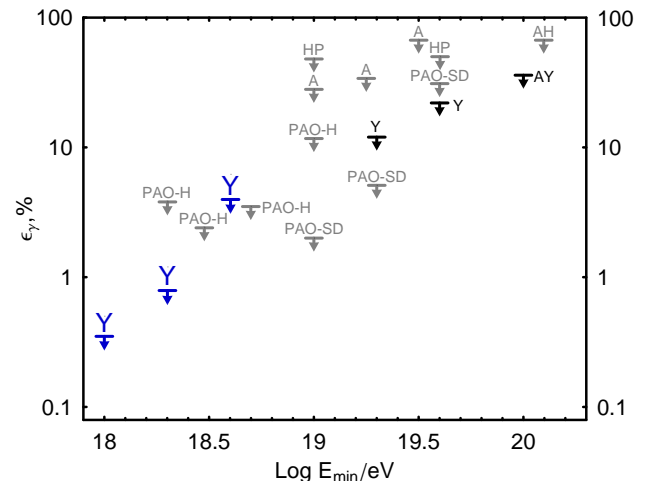


FIG. 1: Limits (95% CL) on the fraction of primary gamma rays in the integral flux of cosmic rays with $E > E_{\min}$ from: this work (large Y); hybrid events of the Pierre Auger Observatory (PAO-H) [41]; the surface detector of the Pierre Auger Observatory (PAO-SD) [42]; Yakutsk (small Y) [32]; reanalyses of the AGASA (AH) [43] and AGASA and Yakutsk (AY) [31] data; AGASA (A) [44] and Haverah Park (HP) [45].

non-photon primary particles. This dependence is weak in the high-statistics regime, cf. Table I.

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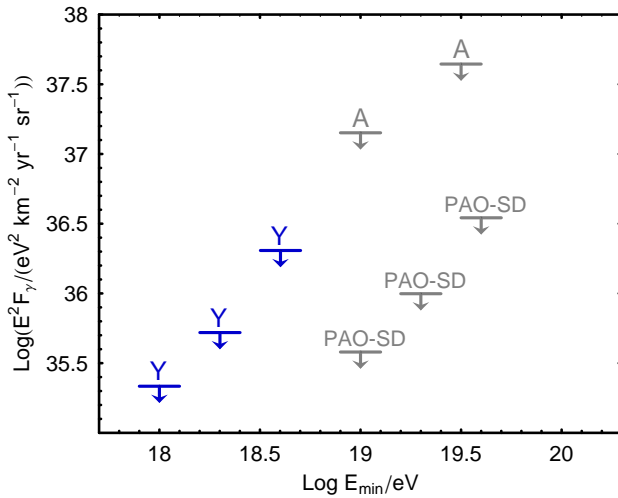


FIG. 2: Limits (95% CL) on the integral flux of primary gamma rays with $E > E_{\min}$ from: this work (Y); the surface detector of the Pierre Auger Observatory (PAO-SD) [42] and AGASA (A; assume mixed proton-gamma composition) [44].

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